Local accuracy of actual intraoral scanning systems for single-tooth preparations in vitro

Zimmermann, Moritz ; Ender, Andreas ; Mehl, Albert

Abstract: BACKGROUND The authors evaluated the local accuracy of intraoral scanning (IOS) systems for single-tooth preparation impressions with an in vitro setup. METHODS The authors digitized a mandibular complete-arch model with 2 full-contour crowns and 2 multisurface inlay preparations with a highly accurate reference scanner. Teeth were made from zirconia-reinforced glass ceramic material to simulate toothlike optical behavior. Impressions were obtained either conventionally (PRESIDENT, Coltène) or digitally using the IOS systems TRIOS 3 and TRIOS 3 using insane scan speed mode (3Shape), Medit i500, Version 1.2.1 (Medit), iTero Element 2, Version 1.7 (Align Technology), CS 3600, Version 3.1.0 (Carestream Dental), CEREC Omnicam, Version 4.6.1, CEREC Omnicam, Version 5.0.0, and Primescan (Dentsply Sirona). Impressions were repeated 10 times per test group. Conventional (CO) impressions were poured with type IV gypsum and digitized with a laboratory scanner. The authors evaluated trueness and precision for preparation margin (MA) and preparation surface (SU) using 3-dimensional superimposition and 3-dimensional difference analysis method using (95% - 5%) / 2 percentile values. Statistical analysis was performed using Kruskal-Wallis test. Results were presented as median (interquartile range) values in micrometers. RESULTS The authors found statistically significant differences for MA and SU among different test groups for both trueness and precision ($P < .05$). Median (interquartile range) trueness values ranged from 11.8 (2.0) m (CO) up to 40.5 (10.9) m (CEREC Omnicam, Version 5.0.0) for SU parameter and from 17.7 (2.6) m (CO) up to 55.9 (15.5) m (CEREC Omnicam, Version 5.0.0) for MA parameter. CONCLUSIONS IOS systems differ in terms of local accuracy. Preparation MA had higher deviations compared with preparation SU for all test groups. PRACTICAL IMPLICATIONS Trueness and precision values for both MA and SU of single-unit preparations are equal or close to CO impression for several IOS systems.

DOI: https://doi.org/10.1016/j.adaj.2019.10.022

Originally published at:
Zimmermann, Moritz; Ender, Andreas; Mehl, Albert (2020). Local accuracy of actual intraoral scanning systems for single-tooth preparations in vitro. Journal of the American Dental Association, 151(2):127-135.
DOI: https://doi.org/10.1016/j.adaj.2019.10.022

Local accuracy of actual intraoral scanning systems for single-tooth preparations in vitro

Dr. Zimmerman is an assistant professor, Division of Computerized Restorative Dentistry, Clinic of Conservative and Preventive Dentistry, Center of Dental Medicine, University of Zurich, Zurich, Switzerland.

Dr. Ender is an associate professor, Division of Computerized Restorative Dentistry, Clinic of Conservative and Preventive Dentistry, Center of Dental Medicine, University of Zurich, Plattenstrasse 11, CH-8032 Zurich, Switzerland,
e-mailandreas.ender@zzm.uzh.ch.
Address correspondence to Dr. Ender.

Dr. Mehl is a professor, Division of Computerized Restorative Dentistry, Clinic of Conservative and Preventive Dentistry, Center of Dental Medicine, University of Zurich, Zurich, Switzerland.

ABSTRACT

Background: Aim of this study was to evaluate the local accuracy of intraoral scanning systems (IOSs) for single tooth preparation impressions with an in vitro setup.

Methods: Lower jaw complete-arch model with two full contour crowns and two multi-surface inlay preparations was digitized with a highly accurate reference scanner. Teeth were made from zirconia reinforced glass ceramic material in order to simulate tooth-like optical behavior. Impressions were performed either conventionally (CO: President) or digitally using IOSs (TRn: Trios3; TRi: Trios3 insane; MD: Medit i500; iT: iTero Element2; CS: CS3600; OC4: CEREC Omnicam v.4.6.1; OC5: CEREC Omnicam v.5.0.0; PS: Primescan) with each n=10. Conventional impressions were poured with type IV gypsum and digitized with a lab scanner. Trueness and precision for preparation margin (MA) and preparation surface (SU) was evaluated using 3D superimposition and 3D difference analysis method using (95-5)/2 percentile values. Statistical analysis was performed with Kruskal-Wallis test. Results are given as median[IQR] values in µm.

Results: Statistically significant differences were found for MA and SU among different test groups for both trueness and precision ($p<0.05$). Trueness values ranged from 11.8[2.0] µm (CO) up to 40.5[10.9] µm (OC5) for parameter SU and from 17.7[2.6] µm (CO) up to 55.9[15.5] µm (OC5) for parameter MA.

Conclusions: IOSs differ in terms of local accuracy. Preparation margin (MA) shows higher deviations compared to preparation surface (SU) for all test groups.

Practical implications: Trueness and Precision values both for MA and SU of single unit preparations are equal or close to conventional impression taking for several IOS systems.

INTRODUCTION

CAD/CAM (Computer-aided-design/computer-aided-manufacturing) technology has gained a significant use in today´s restorative dentistry.[1] Digitalization of tooth geometries with optical devices such as intraoral scanning systems (IOSs) represents the first step within the digital dental workflow. Availability of IOSs has significantly increased in recent years and improvements both in software and hardware components have been realized.[2] Digital impressions with IOSs have been demonstrated to be a clinically acceptable alternative to conventional impression methods for the fabrication of single tooth restorations and short fixed dental prosthesis (FDPs) with limitations still being present for implant supported restorations and edentulous jaws.[3-6] Among the advantages described for IOSs are time efficiency, increased patient comfort and data fusions options within the CAD/CAM workflow.[7-9]

Accuracy of impression methods is crucial for the internal and external fit of the final restoration. Accuracy can be described in terms of trueness and precision and has been measured for IOSs for single abutments, multi-abutment models, complete-arch and edentulous jaw models.[10-15] In literature, different approaches have been described to measure the accuracy of IOSs. Accuracy can be evaluated using indirect 2D/3D approaches by evaluating the fit of restorations.[16,17] Studies regarding the marginal fit of crown restorations have been conducted and misfits of 63.6 µm for restorations derived from IOSs and 58.9 µm for restorations derived from conventional impression workflows have been described in a recent review.[18] Internal marginal discrepancies of below 120 µm have been described to be clinically sufficient for the fit of single tooth restorations.[19] Factors such as the preparation geometry, the CAD design, the CAM milling process and the seating of the restoration have to be considered when evaluating the final fit of the restoration.[18,20,21]

Direct accuracy measurement approaches through linear measurements and 3D difference analysis after best-fit alignment are most commonly used for accuracy evaluation of impression methods.[13,14,22,23] Local accuracy measurements for impression methods can be performed with respect to clinically relevant focus areas such as the preparation margin and the internal fit. Poor marginal fit may favor biofilm accumulation and can cause complications such as secondary caries and periodontal disease.[24] Poor internal adaptation can result in loss of axial retention, missing rotational stability, reduced fracture toughness and positioning inaccuracies leading to interproximal and occlusal interferences.[25]

Digitalization of tooth preparation surface areas with IOSs has been shown to result in alterations of specific geometries such as sharp edges.[26] Difficulties for detection of preparation margins has been reported for IOSs if the margin is located at a close distance from the interproximal neighboring tooth.[27] Confounding factors affecting the margin quality of different IOSs such as neighboring teeth, location of the preparation margin and location of the tooth abutment have been recently demonstrated.[28,29]

The aim of this study was to evaluate the local accuracy of intraoral scanning devices for different tooth preparations with an in vitro setup. The null hypothesis of this study was that there are no statistically significant differences between different impression methods for the local accuracy of tooth preparations.

METHODS

Custom-made lower jaw complete-arch model with teeth made from zirconia reinforced glass ceramic material (Celtra Duo; Dentsply Sirona) was used as a reference model. All teeth were bonded in a fixed position, which ensures that no movement was possible. Glass ceramic material was used to approximate the refractive index of natural teeth.[11,30,31,33] Reference model comprised different types of single tooth preparations. Tooth 41 and 46 were prepared for full contour crowns, tooth 44 for a mesio-occlusal-distal inlay and tooth 36 for a mesio-occlusal inlay. Preparations were performed manually on the reference model in respect to actual preparation parameters for full ceramic restorations.[32] Preparations were done using rotating diamond coated instruments with coarse and fine diamonds under the dental microscope. The absence of undercuts, line angle visibility and wall divergence was verified. **Figure 1** illustrates the reference model with the respective tooth preparations.

Reference model was digitized with a high accurate reference scanner ATOS III Triple Scan MV60; GOM).[33] The reference scanner has been shown to be accurate up to 3 µm and to have a repeatability of 2 µm for scans with the dimensions of full-arches.[34] Impressions were taken from the reference model using one conventional impression technique with polyvinylsiloxane material President (CO) and eight different IOSs. IOSs comprised different hardware and software combinations: Trios3 Pod v.1.18.2.6 using normal scan speed mode (3Shape; [TRn]), Trios3 Pod v.1.18.2.6 using insane scan speed mode (3Shape; [TRi]), CS3600 v.3.1.0 (Carestream Dental; [CS]), Medit i500 v.1.2.1 (Medit; [MD]), iTero Element2 v.1.7 (Align Technology; [iT]) CEREC Omnicam v.4.6.1 (Dentsply Sirona; [OC4]), CEREC Omnicam v.5.0.0 (Dentsply Sirona; [OC5]) and Primescan v.5.0.0 (Dentsply Sirona; [PS]). Impressions were repeated ten times (n=10) per test group. Manufacturers´

recommended scanning strategies were used for all IOSs with specific high-resolution tooth preparation scanning modes used for TRn, CS, iT and MD. All scan data were exported as binary STL-files (standard tessellation language files) for further processing.

Stock metal trays (ASA Permalock; ASA Dental) prepared with VPS universal adhesive (Coltène AG) and polyvinylsiloxane material (President 360 heavy and President light body, Coltène AG) were used for taking conventional impressions of the reference model using a one-step two-viscosity technique. Impressions were repeated ten times (n=10). Impression material setting time was ten minutes and storage time prior to pouring with type IV gypsum (Fujirock EP; GC Corporation,) was eight hours. Storage time for poured model casts was 24 hours. Model casts obtained via conventional impression were subsequently digitized with an extraoral lab scanner (inEos X5; Dentsply Sirona). All scan data was again exported as binary STL-files. **Table 1** shows a summary of the impression methods for all test groups.

In this study, parameters preparation margin (MA) and preparation surface (SU) were evaluated. Data sets were manually cropped for each tooth individually. Preparation margin (MA) was manually determined on the digitized reference model in a 3D CAD software (GOM Inspect 2018 rev 114010; GOM) for each preparation as a spline curve. Preparation surface (SU) was selected as the entire tooth surface within the determined preparation margin line. **Figure 2** exemplarily shows determination of MA and SU for mesio-occlusal inlay preparation of tooth 36.

Before superimposition, the respective preparation surfaces (SU) were selected in all data sets as relevant matching regions. All impression data were then superimposed with the reference data set with a 3D best-fit alignment method and 3D-differences were calculated for each superimposition (GOM Inspect 2018 rev 114010). At the end, 10 difference maps per impression group were available for the calculation of trueness (N=10). Precision was determined in the same way with 3D best-fit alignment and 3D-diffence calculation by superimposing each data set with each other in the respective impression group (N=45). 3D differences were determined by a pointwise signed distance measurement between the respective surfaces (GOM Inspect 2018 rev 114010). For each 3D difference map, the distance values were sorted in a histogram, the 5% and 95% percentile value were determined and the (95-5)/2 value was calculated as a measure for the deviation values.[10,15]. Preparation margin (MA) was calculated as the surface distance measurement under the spline curve, determined as preparation margin at the reference model (GOM Inspect 2018 rev 114010). Normal distribution and equality of variances were tested with Shapiro Wilk and Levene´s test and statistical analysis was performed with Kruskal-Wallis test with adapted significance levels using statistical analysis software (SPSS v.25; IBM).

RESULTS

The of MA and SU were first evaluated separately for inlay and crown preparations. This evaluation did not reveal differences between the different preparation types within the respective test groups. Data for parameter MA and SU was subsequently pooled for all 4 preparations in terms of trueness and precision values for statistical analysis. Results for trueness and precision values of preparation margin (MA) and preparation surface (SU) indicated as median[IQR] (interquartile range) and mean±SD are shown in **Table 2** and **Figure 3**. Statistically significant differences were found for both parameters MA and SU among different test groups for trueness and precision ($p<0.05$). For parameter SU, precision values ranged from 8.3[2.4] µm (PS) up to 23.9[8.8] µm (OC5) and trueness values ranged from 11.8[2.0] µm (CO) up to 40.5[10.9] µm (OC5). For parameter MA, precision values ranged from 14.3[9.0] µm (CO) up to 48.8[24.4] µm (OC5) and trueness values ranged from 17.7[2.6] µm (CO) up to 55.9[15.5] µm (OC5). Conventional impression method (CO) showed higher trueness with 11.8[2.0] µm (parameter SU) and 17.7[2.6] µm (parameter MA) than all tested IOSs for single tooth preparation impressions. Statistically significant differences were found to all IOSs except PS. IOSs showed great variability in terms of trueness and precision for preparation margin (MA) and preparation surface (SU). Within the IOSs, group PS showed higher trueness with 19.4[5.0] µm for parameter SU with values being statistically significant different to all IOSs except TRn and Tri. Group PS showed also higher trueness with 21.4[2.7] µm for parameter MA with statistically significant differences to all IOSs. For precision values, best values with 8.3[2.4] µm for parameter SU were found for group PS with statistically significant differences to all IOSs. For parameter MA precision of PS and CO did not show any statistically significant differences.

DISCUSSION

In this study, local accuracy of conventional and digital impression methods for different single tooth preparation geometries was evaluated in vitro using a custom-made reference model. There were eight different IOS setups comprising different hardware and software combinations and one conventional impression method using polyvinylsiloxane material as a control group. Evaluation of accuracy was performed using superimposition method with best-fit alignment of digitized models and difference analysis with a 3D difference analysis software using (95-5)/2 percentile values. Results varied statistically significantly among different test groups ($p<0.05$). Based on the findings of this study, the null hypothesis that there are no statistically significant differences between different impression methods for local accuracy of tooth preparations has to be rejected. Results of this study need to be discussed under various aspects.

In this study, local accuracy of impression methods for single tooth crown and inlay preparations was evaluated using an in vitro test setup model with specific model characteristics. Teeth were fabricated from zirconia reinforced lithium silicate ceramic material Celtra Duo (Dentsply Sirona) to imitate tooth like translucency and reflectivity.[30,31,35] Gingiva material was fabricated from conventional PMMA material with preparation margins being located supragingival for all preparations. Scanning accuracy of IOSs might be influenced by model characteristics and subsurface scattering and light travelling through different media.[11] The idea of creating the present custom-made model was to scan from a surface with a refraction index close to the natural dentition. However, this does not display the real optical properties of teeth and the results of the study additionally lack adverse clinical factors for IOSs such as subgingival preparation margins, presence of gingival crevicular fluid, humidity through breathing, saliva, patient movement and a limited access as a result of anatomical structures. Further in vivo studies might be thus necessary to support findings of this study also for more challenging clinical application of IOSs. However, results of this in vitro study give a first assessment of the different quality of the digitalization process for different IOSs in terms of objects with specific geometries such as preparation margins and translucent optical characteristics. Beyond this aspect, parameter trueness is only quantifiable using in vitro test setups.

Internal fit of restorations plays a predominant role in the long-term success of indirect restorations.[24,25] High precise digitalization of tooth abutments is thus an important step within the digital restorative CAD/CAM workflow. All median values for parameters MA and SU for all IOSs evaluated in this study were in range or better than the clinically recommended threshold of 120 µm for the fit of indirect restorations.[19] In this study, trueness values for parameter SU ranged from 11.8[2.0] µm for group (CO) to 40.5[10.9] µm for group (OC5). Specific IOSs show an equal accuracy level of highly accurate impression materials for parameter SU. When comparing values found for parameters SU and MA it is important to emphasize that results for SU are less influenced by possible inaccuracies of the impression method since specific localized deviations represent only a small part of the entire surface data set.

Both trueness and precision values for parameter MA showed higher deviations compared to parameter SU for all groups. Trueness values for parameter MA ranged from 14.3[9.0] µm for group (CO) to 48.8[24.4] µm for group (OC5). Group (PS) shows no statistically significant differences to group (CO) for parameter MA in terms of trueness and parameter SU in terms of precision. When evaluating local accuracy of tooth abutments, parameter preparation margin (MA) might be a crucial clinical parameter. Positive deviations for the preparation margin line might result in restorations being too short on the preparation. Negative deviations for the preparation margin line might result in restorations with premature contacts and as a result of restorations being stuck to the abutment. Results of this study support findings of previous studies that report from difficulties for IOSs in the exact reproduction of preparation margin.[26-29] Nedelcu et al. qualitatively reported from rounding of sharp preparation angles for specific IOSs.[26] Ferrari et al. demonstrated the appearance of bridging effects for IOSs if distances to neighboring teeth are too close.[27]

In this study, local accuracy for tooth preparations was measured using parameters trueness and precision. Trueness is obtained by comparing the reference master model cast with the digitized model casts. Precision is obtained by intragroup comparison of digitized model casts. Precision values for parameters SU and MA were lower than the respective trueness values for all test groups. Whereas results for trueness show the deviation from the reference geometry, results for precision values for parameters SU and MA show the different variability of IOSs in digitizing tooth abutment geometries. Variability in local accuracy for IOSs might be caused by varying acquisition techniques and software algorithms that are used by the different IOSs. When comparing trueness and precision values for the different test groups, no systematic failures were evident.

In this study, values were pooled for different tooth preparation types (tooth 46,44,41 and 36) to evaluate trueness and precision values for the different impression methods. Studies have shown that the accuracy of IOSs might be influenced by the abutment tooth geometry and its location.[28,36] Marginal fit of CAD/CAM restorations has been shown to be influenced also by the type of tooth preparation.[37] Aim of this study was to give an evaluation for the local accuracy of impression methods for typical inlay and full crown preparations used within the CAD/CAM workflow for single unit restorations. Tooth preparation indications were thus selected with different locations and different preparation dimensions. Data analysis within this study setup revealed no differences for these different preparation types.

Results of the present study can be compared with results previously published for the local accuracy of impression methods for single tooth preparations. Carbajal Mejia et al. report trueness values of 19.1±2.0 µm and precision values of 11.9±2.3 µm using IOS Trios.[36] Lee et al. report trueness value of 13.8±1.4 µm and precision values of 12.5±3.7 µm for IOS CEREC Omnicam.[38] Different values reported in different studies can be explained by different study design and different 3D difference evaluation methods (RMS vs. percentiles).

Several studies regarding the fit of crown restorations have been conducted and marginal misfits of 63.6 µm for restorations derived from IOSs and 58.9 µm for restorations derived from conventional impression workflows have been described in a recent review.[18] It is important to emphasize that values for restoration fit are not identical with accuracy values for local tooth preparation impression methods since they exclude summarizing errors deriving from the previous steps of the CAD/CAM workflow. When evaluating the final fit of restorations, all contributing factors such as the CAD design, the CAM milling process and the seating of the restoration have to be considered.[18] The present results on the local accuracy of different impression methods do not provide any information about its influence on the fit of definitive restorations.

CONCLUSION

IOSs show different behaviors in terms of local accuracy. Preparation margin (MA) shows higher deviations compared to preparation surface (SU) for all test groups. Trueness and Precision values both for MA and SU of single unit preparations are equal or close to conventional impression taking for several IOS systems.

REFERENCES

1. Mormann WH. The evolution of the CEREC system. J Am Dent Assoc 2006;137 Suppl:7s-13s.
2. Zimmermann M, Mehl A, Mormann WH, Reich S. Intraoral scanning systems - a current overview. Int J Comput Dent 2015;18(2):101-29.
3. Ahlholm P, Sipila K, Vallittu P, Jakonen M, Kotiranta U. Digital Versus Conventional Impressions in Fixed Prosthodontics: A Review. J Prosthodont 2018;27(1):35-41.
4. Patzelt SB, Vonau S, Stampf S, Att W. Assessing the feasibility and accuracy of digitizing edentulous jaws. J Am Dent Assoc 2013;144(8):914-20.
5. Fang JH, An X, Jeong SM, Choi BH. Digital intraoral scanning technique for edentulous jaws. J Prosthet Dent 2018;119(5):733-735.
6. Vandeweghe S, Vervack V, Dierens M, De Bruyn H. Accuracy of digital impressions of multiple dental implants: an in vitro study. Clin Oral Implants Res 2017;28(6):648-653.
7. Patzelt SB, Lamprinos C, Stampf S, Att W. The time efficiency of intraoral scanners: an in vitro comparative study. J Am Dent Assoc 2014;145(6):542-51.
8. Yuzbasioglu E, Kurt H, Turunc R, Bilir H. Comparison of digital and conventional impression techniques: evaluation of patients' perception, treatment comfort, effectiveness and clinical outcomes. BMC Oral Health 2014;14:10.
9. Reich S, Vollborn T, Mehl A, Zimmermann A. Intraoral optical impression systems--an overview. Int J Comput Dent 2013;16(2):143-62.
10. Ender A, Mehl A. Accuracy of complete-arch dental impressions: a new method of measuring trueness and precision. J Prosthet Dent 2013;109(2):121-8.
11. Nedelcu RG, Persson AS. Scanning accuracy and precision in 4 intraoral scanners: an in vitro comparison based on 3-dimensional analysis. J Prosthet Dent 2014;112(6):1461-71.

12. Gonzalez de Villaumbrosia P, Martinez-Rus F, Garcia-Orejas A, Salido MP, Pradies G. In vitro comparison of the accuracy (trueness and precision) of six extraoral dental scanners with different scanning technologies. J Prosthet Dent 2016;116(4):543-550.e1.

13. Guth JF Runkel C, Beuer F, Stimmelmayr M, Edelhoff D, Keul C. Accuracy of five intraoral scanners compared to indirect digitalization. Clin Oral Investig, 2017. 21(5): p. 1445-1455.

14. Ender A, Mehl A. Full arch scans: conventional versus digital impressions--an in-vitro study. Int J Comput Dent 2011;14(1):11-21.

15. Ender A, Mehl A. In-vitro evaluation of the accuracy of conventional and digital methods of obtaining full-arch dental impressions. Quintessence Int 2015;46(1):9-17.

16. Boitelle P, Mawussi B, Tapie L, Fromentin O. A systematic review of CAD/CAM fit restoration evaluations. J Oral Rehabil 2014;41(11):853-74.

17. Prudente MS, Davi LR, Nabbout KO, Prado CJ, Pereira LM, Zancopé K, Neves FD. Influence of scanner, powder application, and adjustments on CAD-CAM crown misfit. J Prosthet Dent 2018;119(3):377-383.

18. Tsirogiannis P, Reissmann DR, Heydecke G. Evaluation of the marginal fit of single-unit, complete-coverage ceramic restorations fabricated after digital and conventional impressions: A systematic review and meta-analysis. J Prosthet Dent 2016;116(3):328-335.e2.

19. McLean JW, von Fraunhofer JA. The estimation of cement film thickness by an in vivo technique. Br Dent J 1971;131(3):107-11.

20. Hmaidouch R, Neumann P, Mueller WD. Influence of preparation form, luting space setting and cement type on the marginal and internal fit of CAD/CAM crown copings. Int J Comput Dent 2011;14(3):219-26.

21. Boitelle P, Tapie L, Mawussi B, Fromentin O. 3D fitting accuracy evaluation of CAD/CAM copings - comparison with spacer design settings. Int J Comput Dent 2016;19(1):27-43.
22. Patzelt SB, Emmanouilidi A, Stampf S, Strub JR, Att W. Accuracy of full-arch scans using intraoral scanners. Clin Oral Investig 2014;18(6):1687-94.
23. Guth JF, Edelhoff D, Schweiger J, Keul C. A new method for the evaluation of the accuracy of full-arch digital impressions in vitro. Clin Oral Investig 2016;20(7):1487-94.
24. Contrepois M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: a systematic review. J Prosthet Dent 2013;110(6):447-454.e10.
25. Wettstein F, Sailer I, Roos M, Hammerle CH. Clinical study of the internal gaps of zirconia and metal frameworks for fixed partial dentures. Eur J Oral Sci 2008;116(3):272-9.
26. Nedelcu R, Olsson P, Nystrom I, Thor A. Finish line distinctness and accuracy in 7 intraoral scanners versus conventional impression: an in vitro descriptive comparison. BMC Oral Health 2018;18(1):27.
27. Ferrari M, Keeling A, Mandelli F, Lo Giudice G, Garcia-Godoy F, Joda T. The ability of marginal detection using different intraoral scanning systems: A pilot randomized controlled trial. Am J Dent 2018;31(5):272-276.
28. Keeling A, Wu J, Ferrari M. Confounding factors affecting the marginal quality of an intra-oral scan. J Dent 2017;59:33-40.
29. Oh KC, Lee B, Park YB, Moon HS. Accuracy of Three Digitization Methods for the Dental Arch with Various Tooth Preparation Designs: An In Vitro Study. J Prosthodont 2018; doi:10.1111/jopr.12998 [Epub ahead of print].

30. Meng Z, Yao XS, Yao H, Liang Y, Liu T, Li Y, Wang G, Lan S. Measurement of the refractive index of human teeth by optical coherence tomography. J Biomed Opt 2009; 14:034010.

31. Latham J, Ludlow M, Mennito A, Kelly A, Evans Z, Renne, W. Effect of scan pattern on complete-arch scans with 4 digital scanners. J Prosthet Dent 2019 doi: 10.1016/j.prosdent.2019.02.008. [Epub ahead of print].

32. Ahlers MO, Morig G, Blunck U, Hajto J, Probster L, Frankenberger R. Guidelines for the preparation of CAD/CAM ceramic inlays and partial crowns. Int J Comput Dent 2009;12(4):309-25.

33. Renne W, Ludlow M, Fryml J, Schurch Z, Mennito A, Kessler R, Lauer A. Evaluation of the accuracy of 7 digital scanners: An in vitro analysis based on 3-dimensional comparisons. J Prosthet Dent 2017;118(1):36-42.

34. Dold P, Bone MC, Flohr M, Preuss R, Joyce TJ, Deehan D, Holland J. Validation of an optical system to measure acetabular shell deformation in cadavers. Proc Inst Mech Eng H 2014;228(8):781-6.

35. Della Bona A, Nogueira AD, Pecho OE. Optical properties of CAD-CAM ceramic systems. J Dent 2014;42(9):1202-9.

36. Carbajal Mejia JB, Wakabayashi K, Nakamura T, Yatani H. Influence of abutment tooth geometry on the accuracy of conventional and digital methods of obtaining dental impressions. J Prosthet Dent 2017;118(3):392-399.

37. Lima FF, Neto CF, Rubo JH, Santos GC, Moraes Coelho Santos MJ. Marginal adaptation of CAD-CAM onlays: Influence of preparation design and impression technique. J Prosthet Dent 2018;120(3):396-402.

38. Lee JJ, Jeong ID, Park JY, Jeon JH, Kim JH, Kim WC. Accuracy of single-abutment digital cast obtained using intraoral and cast scanners. J Prosthet Dent 2017;117(2):253-259.

LEGENDS

Figure 1: Customized complete-arch lower jaw reference model with teeth made from zirconia reinforced lithium silicate ceramic material (Celtra Duo, Dentsply Sirona); local accuracy of impression methods was analyzed for full contour crown preparations on tooth 46 (A) and 41 (C) and mesio-occlusal-distal inlay preparation on tooth 44 (B) and mesio-occlusal inlay preparation on tooth 36 (D).

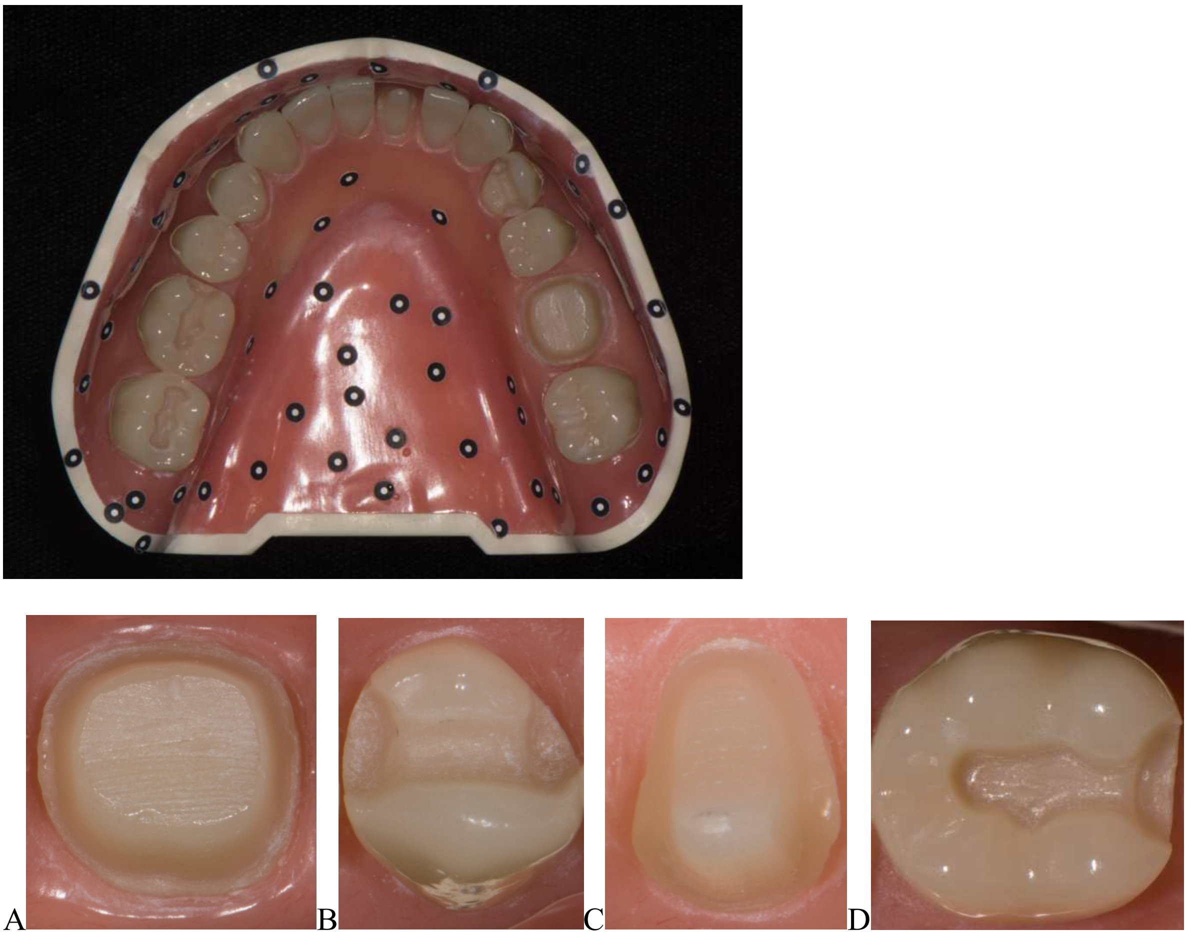

Figure 2: Visualization of parameters used for the evaluation of local accuracy of conventional and digital impressions methods for single tooth preparations; parameter preparation margin (MA) highlighted in red and preparation surface (SU) highlighted in blue; example shown for mesio-occlusal inlay preparation of tooth 36.

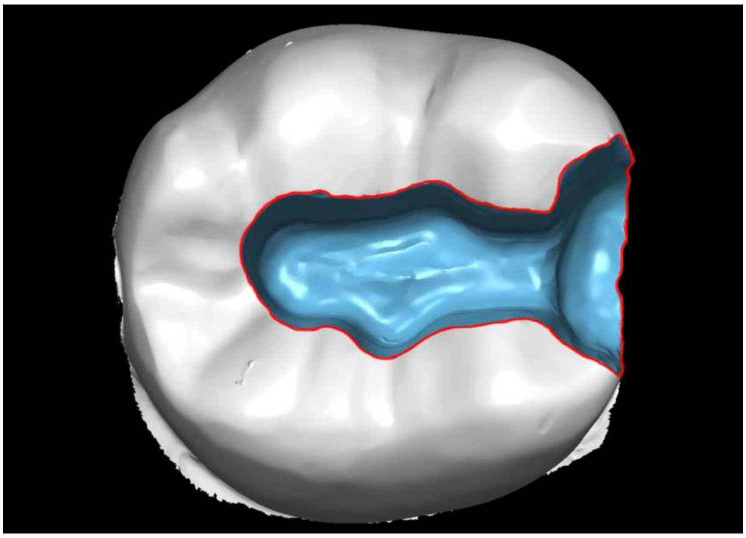

Figure 3: Boxplot diagrams for trueness and precision values of conventional and digital impressions methods for local accuracy of tooth preparations using (95-5)/2 percentile values; values in µm; parameter preparation surface (SU) and preparation margin (MA); box represents IQR range; bar within box represents median value.

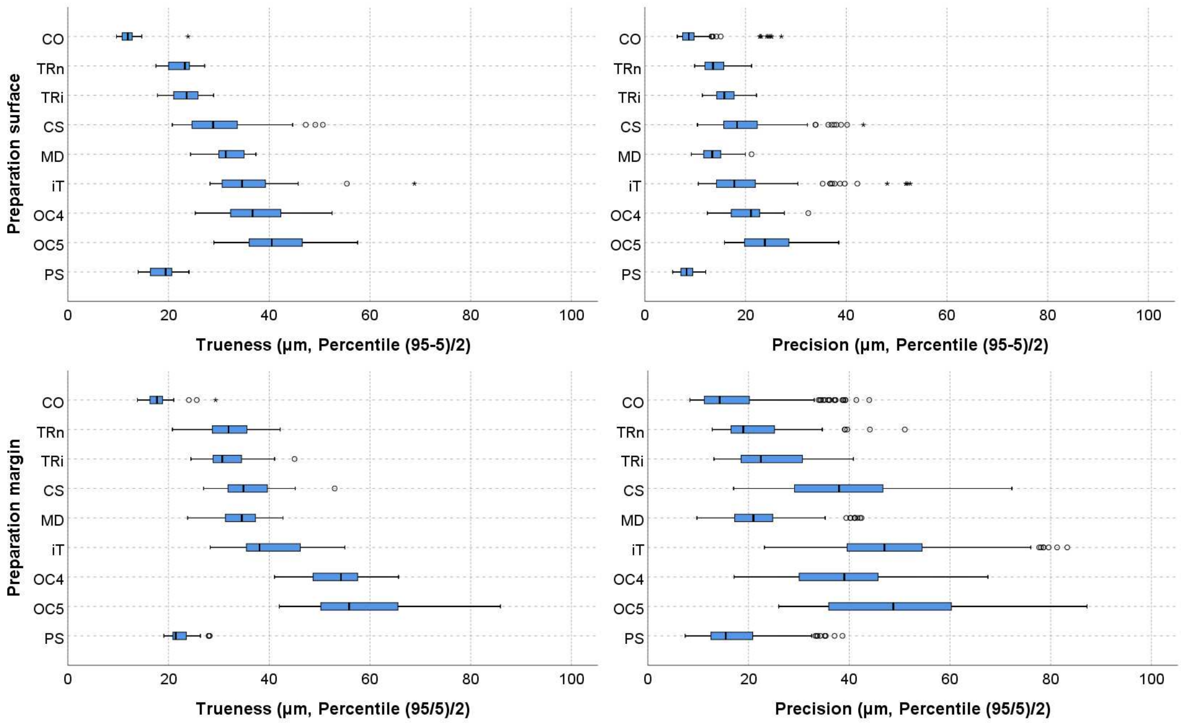

Table 1: Test groups including indication of software versions, manufacturers and post-processing protocols to obtain STL data sets for the evaluation of accuracy of impression methods for local accuracy of tooth preparations.

Test group	System	Manufacturer	Software	Post-processing
CO	President 360 Heavy Body + President Light Body	Coltène AG	not applicable	Poured with type IV gypsum, digitized with inEOS X5, direct export to STL
TRn	Trios3 normal scan mode	3Shape	Trios3 Software v. 1.18.2.6	Direct export to STL
TRi	Trios3 insane speed scan mode	3Shape	Trios3 Software v. 1.18.2.6	Direct export to STL
CS	CS3600	Carestream Dental	CS IO 3D Acquisition Software v. 3.1.0	Direct export to STL
MD	Medit i500	Medit	Medit Link v. 1.2.1	Direct export to STL
iT	iTero Element2	Align Technology	iTero Element2 Software v. 1.7	Direct export to STL
OC4	CEREC Omnicam	Dentsply Sirona	CEREC Software v. 4.6.1	Direct export to STL
OC5	CEREC Omnicam	Dentsply Sirona	CEREC Software v. 5.0.0	Direct export to STL
PS	Primescan	Dentsply Sirona	CEREC Software v. 5.0.0	Direct export to STL

Table 2: Results for trueness and precision values of conventional and digital impressions methods for local accuracy of tooth preparations using (95-5)/2 percentile values; values in µm; parameter preparation surface (SU) and preparation margin (MA); values indicated as median[IQR] and mean±SD; values in µm; values with the same superscript letter within the same column indicate non-statistically significant differences (Kruskal-Wallis test for non-normal distributed data, adapted significance levels).

Trueness (Median[IQR]/MEAN±SD, µm, Percentile (95-5)/2)						
	Preparation surface (SU)			Preparation margin (MA)		
Group	Median[IQR]	MEAN±SD		Median[IQR]	MEAN±SD	
CO	11.8 [2.0]	12.2±2.3	A	17.7 [2.6]	18.2±3.0	A
TRn	23.3 [4.2]	22.6±2.7	B,D	31.9 [7.0]	32.0±4.8	B,E,F
Tri	23.6 [5.4]	23.6±3.0	C,D	30.7 [6.0]	31.5±4.6	B,C,D
CS	28.9 [9.4]	31.1±7.9	E,F,G	34.9 [8.4]	35.8±6.0	C,F,G,I
MD	31.4 [5.1]	32.0±3.2	E,H	34.5 [6.2]	34.6±4.3	D,E,G,H
iT	34.6 [8.6]	36.3±7.8	F,H,I,K	38.1 [11.1]	40.0±6.9	H,I
OC4	36.7 [10.1]	36.6±6.4	G,I,L	54.3 [9.0]	53.4±6.2	L
OC5	40.5 [10.9]	41.7±7.0	K,L	55.9 [15.5]	58.0±10.6	L
PS	19.4 [5.0]	18.7±2.8	A,B,C	21.4 [2.7]	22.4±2.4	A

Precision (Median[IQR]/MEAN±SD, µm, Percentile (95-5)/2)						
	Preparation surface (SU)			Preparation margin (MA)		
Group	Median[IQR]	MEAN±SD		Median[IQR]	MEAN±SD	
CO	8.7 [2.2]	9.5±3.9	A	14.3 [9.0]	17.7±8.8	A
TRn	13.6 [3.8]	14.0±2.4	B	18.9 [8.7]	21.2±6.7	B,C,D
Tri	15.8 [3.5]	16.0±2.3	C	22.5 [12.4]	24.4±6.9	C,E
CS	18.3 [6.7]	19.5±6.1	D,F	38.0 [17.7]	38.5±12.0	F
MD	13.4 [3.4]	13.6±2.5	B	21.0 [7.6]	21.6±6.9	D,E
iT	17.8 [7.7]	19.6±8.0	C,D,E	47.0 [14.9]	47.6±11.3	G
OC4	21.1 [6.0]	20.3±4.0	E,F	39.0 [15.7]	38.5±10.6	F
OC5	23.9 [8.8]	24.7±5.3	G	48.8 [24.4]	50.2±15.4	G
PS	8.3 [2.4]	8.3±1.5	A	15.5 [8.4]	17.9±7.6	A,B